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Report to the Chair, Government Activities and Transportation Subcommittee, Committee on Government Operations, House of Representatives

July 1992

SPACE STATION

Improving NASA's Planning for External Maintenance

GAO

United States
General Accounting Office
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National Security and
International Affairs Division

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July 20, 1992

The Honorable Barbara Boxer
Chair, Government Activities and
Transportation Subcommittee
Committee on Government Operations
House of Representatives

Dear Madam Chair:

As requested, we reviewed the National Aeronautics and Space Administration's (NASA) efforts to determine the extent of external maintenance on Space Station Freedom that will need to be performed by space-walking astronauts and NASA's planning to meet those requirements. This report contains recommendations to the NASA Administrator.

We plan no further distribution of this report until 30 days from the date of this letter, unless you publicly announce its contents earlier. At that time, we will send copies to the NASA Administrator and appropriate congressional committees. Copies will also be made available to others on request.

Please contact me on (202) 275-5140 if you or your staff have any questions concerning this report. The major contributors to this report are listed in appendix I.

Sincerely yours,

Mark E. Gebicke

Mark E. Gebicke
Director, NASA Issues

Space Station
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for External Maintenance

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Executive Summary

Purpose

In 1996, the National Aeronautics and Space Administration (NASA) plans to begin assembly of the international Space Station Freedom in low earth orbit. One of the greatest challenges facing NASA will be maintaining the space station's external components throughout the assembly period and over its anticipated 30-year life using astronauts to perform space walks—referred to as extravehicular activity (EVA). The amount of EVA that can be performed is limited, and the activity is inherently risky, given the harsh environment of space.

At the request of the Chair of the Government Activities and Transportation Subcommittee, House Committee on Government Operations, GAO reviewed NASA's efforts to determine the space station's EVA maintenance requirements and its planning to meet those requirements.

Background

Four years and 17 space shuttle flights are planned to assemble the space station, a multibillion dollar orbiting research facility. In 1997, after six assembly flights, NASA expects that the space station will have reached crew-tended capability, when shuttle crews can begin research activities. Eight "utilization" flights, in addition to the ongoing assembly flights, are planned during this phase. The space shuttle crews on these utilization flights are to begin conducting research in life sciences, material processing, technology development, and other activities. NASA plans to permanently staff the station in 2000, when four-person crews will begin to live and work on the facility.

In late 1989, NASA made the first of several estimates of the space station's EVA maintenance requirements, expressed as the annual average EVA crew-hours needed to maintain the space station. Early estimates predicted that external maintenance could require thousands of EVA crew-hours each year. The estimates decreased after the space station was redesigned to its current configuration in 1991. The new space station is smaller, less complex, and has fewer components requiring EVA maintenance. NASA recently estimated that, on average, under very favorable circumstances, annual external maintenance could require as few as 135 EVA crew-hours; under less favorable circumstances, up to 384 crew-hours.

Results in Brief

External maintenance for the space station will be a formidable challenge. NASA has limited assurance that the primary data used in estimating EVA

maintenance requirements are reasonably accurate. In part, this is due to the early development status of the program and the limitations of currently available methods for estimating failure rates and replacement times. Also, the scope and depth of NASA's review of the contractors' failure rate and replacement time estimates are insufficient to ensure the quality of these data.

EVA resources will not be adequate for dealing with all the external maintenance needs predicted to develop during the station's assembly period, and a large maintenance backlog may accumulate. NASA's analyses of the backlog's impact on the station's performance are not yet completed. Thus, maintenance planners do not yet know which maintenance needs can be deferred. In addition, the maintenance backlog may be understated because of inconsistencies in the assumptions about EVA availability for planning maintenance, assembly, and research activities throughout the station's assembly period. Ultimately, extra shuttle flights could be added specifically to perform maintenance, although this would increase program costs and, perhaps, delay the assembly and use of the space station, or delay other non-station shuttle missions. Program officials expect to have better assembly and maintenance estimates on which to base their allocations of EVA resources by the time the program's critical design review is completed next summer.

After assembly is completed, the amount of time available for EVA maintenance will be less constrained. NASA currently budgets 252 space station crew-hours each year for EVA and 329 crew-hours for using remotely controlled robots to perform some external maintenance. In addition, the shuttle crew will perform EVA maintenance during its quarterly visits to the station. However, if EVA maintenance requirements are higher than predicted, the time available for research activities could be reduced.

Principal Findings

External Maintenance Requirements Are Uncertain

Because space station components have not yet been built, their failure rates and replacement times are estimates based upon models and engineering judgments. While these approaches may be the best currently available, their accuracy is uncertain. For example, the models used to

predict failure rates do not tell the user how much confidence can be placed in the estimates and do not take into account extrinsic factors, such as human error, which can impact the failure rates. NASA's current adjustment for such extrinsic factors provides a smaller margin for error than did previous estimates. In developing component replacement times, NASA bases its estimates on a variety of sources that may or may not have direct relevance to the space station because it does not yet have all the external space station component "mock-ups" needed to time the simulation of replacement activities. Further, some uncertainty will always exist in the replacement time estimates because of the difficulty in simulating space operations.

NASA does not routinely conduct detailed reviews of contractor data to determine if the sources and assumptions underlying the failure rates and replacement times are reasonable. NASA's review teams scan the data for obvious errors or inconsistencies, but they limit further scrutiny of the data to those items that, in their judgment, appear to be incorrect. Program officials contend that they lack the resources to perform more extensive review of the data, but believe that the most important items are reviewed. Nevertheless, they agreed that their review process can allow errors to go undetected.

To the extent that uncertainty exists in the failure rate and replacement time estimates, EVA maintenance requirements are also uncertain. While some aspects of NASA's estimating process provide a margin for error in the EVA requirements predicted, it is unclear that the margin provided is sufficient to offset the degree to which the failure rate and replacement time estimates could be understated.

EVA Maintenance Will Be Backlogged During Assembly Phase

Before the space station's assembly is completed, many parts are predicted to fail. Because of the limited amount of EVA time available for maintenance during the assembly period, NASA plans to defer non-critical maintenance and allow the accumulation of a maintenance backlog that could become quite large. Maintenance planners have developed EVA maintenance demand estimates, but they have not yet completed their analyses of the impact of backlogged component failures on the performance of the space station.

Maintenance planners may be understating the size of the backlog because they assume that EVA crew-hours will be available for maintenance on the shuttle's assembly flights and utilization flights. Currently, all EVA time on

the assembly flights is earmarked for assembly tasks, and no EVA time is scheduled on the utilization flights. Only if EVA time remains after assembly tasks are completed, or if time exists between assembly tasks, will any be used for maintenance. Program officials said that EVA could be added to the assembly flights if necessary. In addition, some EVA maintenance could be done by shuttle crews visiting the station on utilization flights. However, performing maintenance will limit the amount of time for research, the purpose for which the Congress directed these flights. If sufficient EVA maintenance time is not available on assembly and utilization flights, shuttle flights would need to be added specifically for maintenance, an action that would increase program costs and also delay assembly and use of the station.

After assembly is completed and the space station is permanently staffed, the amount of EVA time available for maintenance will increase. When the visiting shuttle is present, NASA will use the shuttle crew to perform EVA maintenance on the space station. In addition, NASA currently budgets about 252 space station crew-hours each year for performing EVA maintenance and 329 crew-hours for using remotely controlled robots to perform some external maintenance tasks.

Recommendations

GAO recommends that the NASA Administrator direct that

- contractor data used to develop EVA maintenance demand estimates be reviewed in sufficient scope and depth to provide better assurance of their accuracy and
- before the completion of the station's critical design review, appropriate steps be taken to eliminate inconsistent assumptions in maintenance, assembly, and utilization plans concerning the availability of EVA maintenance time during the station's assembly phase.

Agency Comments

As requested, GAO did not obtain written agency comments on this report. However, GAO discussed the results of its review with space station program managers, who generally concurred with the findings. Their comments have been incorporated where appropriate.

Contents

Abbreviations

EVA	extravehicular activity
GAO	General Accounting Office
NASA	National Aeronautics and Space Administration
RMAT	Reliability and Maintainability Assessment Tool

Chapter 1

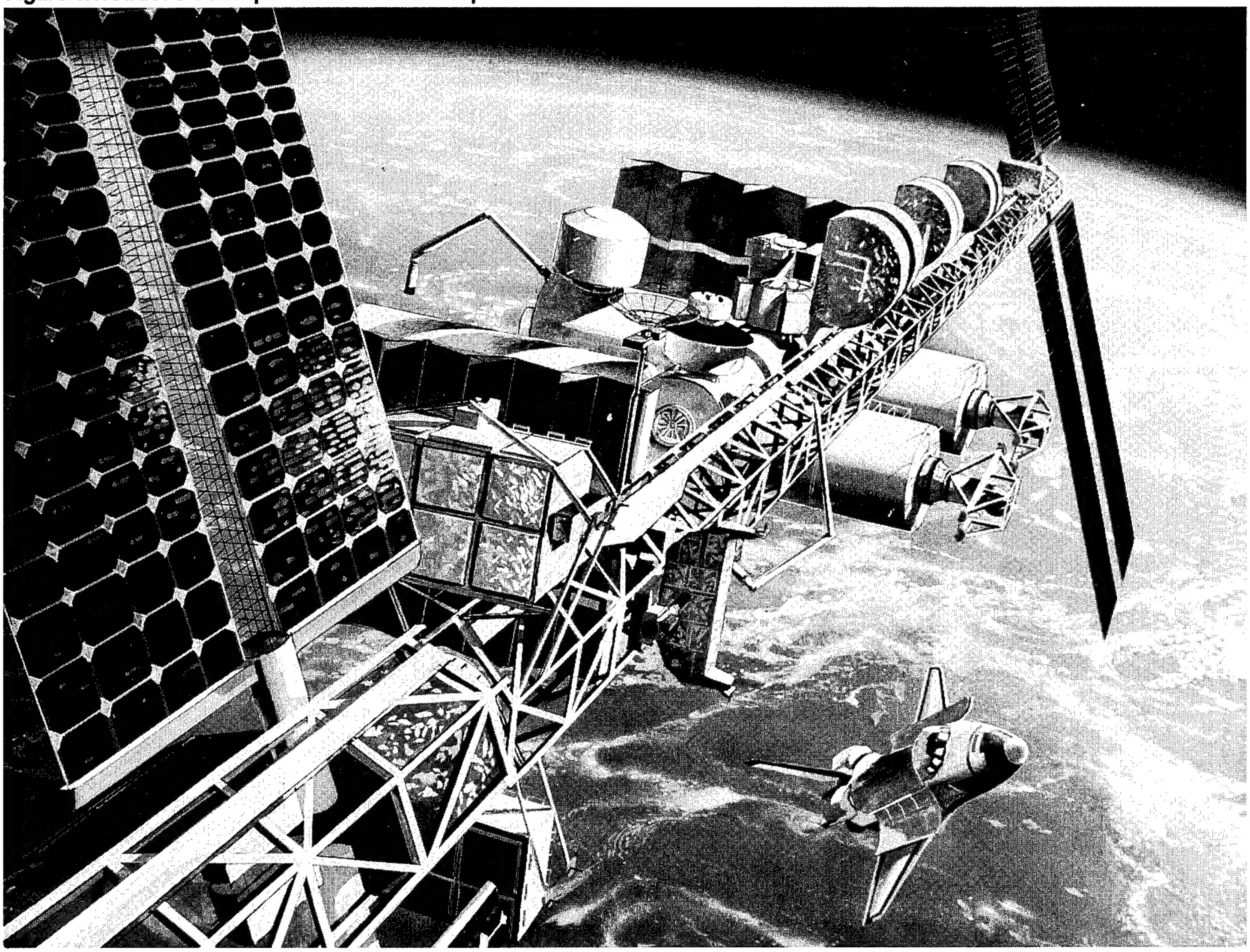
Introduction

In 1996, the National Aeronautics and Space Administration (NASA) plans to launch the first segment of Space Station Freedom, an international, multibillion dollar research facility and the cornerstone of NASA's manned space program. Over a 4-year period, space-walking astronauts on 17 space shuttle flights will assemble the space station about 220 miles above the earth. After its assembly is completed, the space station is expected to operate for 30 years.

The space station's current configuration (see fig. 1.1) is the product of the program's fourth major redesign effort since the program was initiated by the President in January 1984.[1] The space station design will be finalized by the completion of the program's critical design review in the summer of 1993. At that point, space station contractors will begin manufacturing and testing space station components in accordance with the final design.

[1] Space Station: NASA's Search for Design, Cost, and Schedule Stability Continues (GAO/NSIAD-91-125, Mar. 1, 1991).

Figure 1.1: Artist's Conception of the Planned Space Station



Source: NASA.

As part of the 1991 redesign effort, Congress directed that NASA develop a phased approach so the space station would be useful for research activities well before it was completely assembled. The redesigned space station is intended to begin operating as a research facility when it reaches

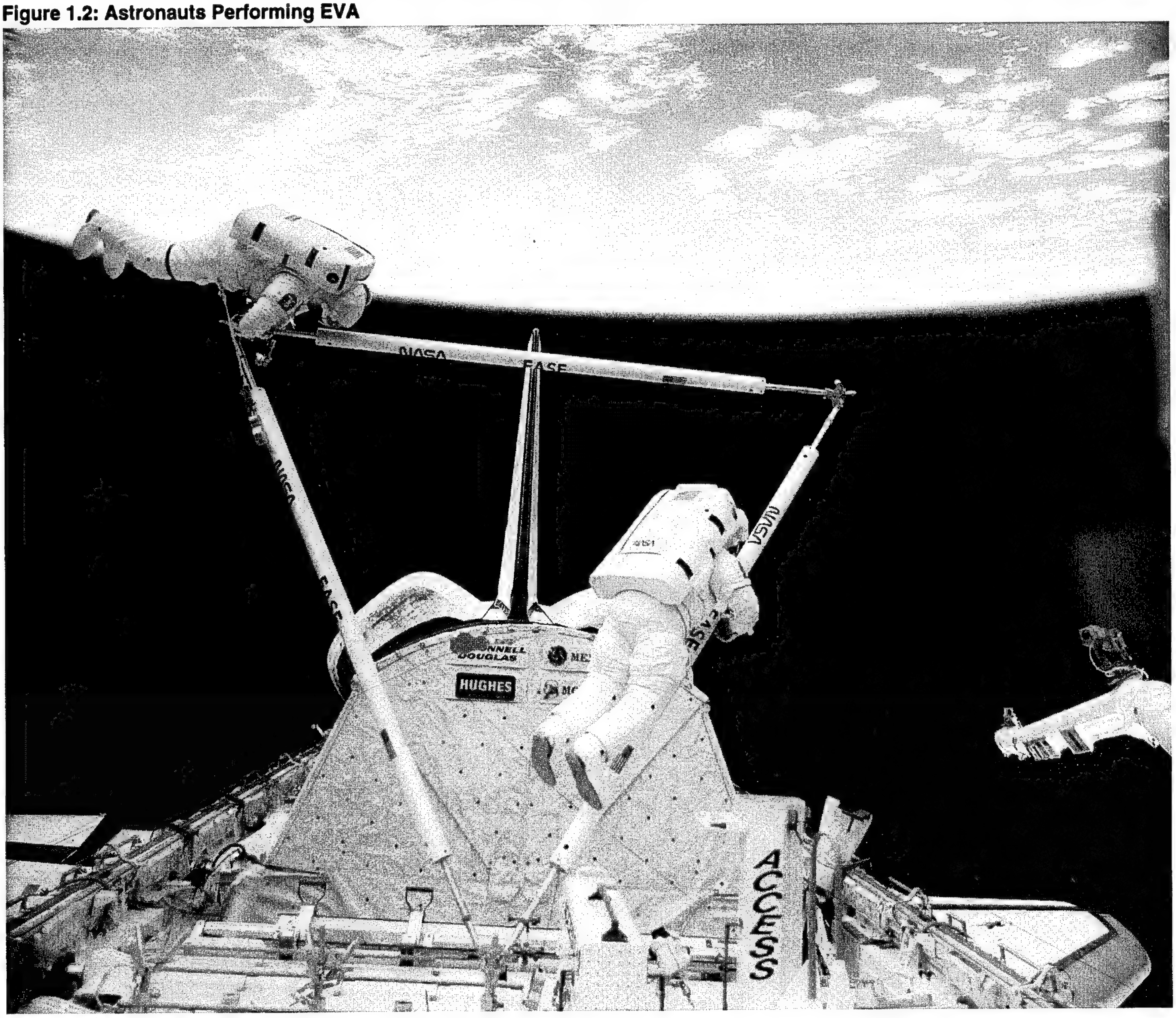
crew-tended capability after the sixth shuttle assembly flight, currently scheduled for no later than March 1997. During crew-tended capability, the shuttle will make eight "utilization" flights to the station to do research in life sciences, materials processing, technology development, and other areas. After the 17th shuttle assembly flight, scheduled for no later than September 2000, NASA expects to have achieved permanently staffed capability, at which time 4-person crews will begin to live and work in the space station for extended periods of time.

Space Walks Will Be Required for External Maintenance

The space station represents a new and significant challenge for NASA because it must be maintained primarily in space throughout its anticipated 30-year life. All maintenance will be performed by the shuttle crews who visit the space station during its assembly and crew-tended phases and by visiting shuttle crews and the four-person crews living there after it is permanently staffed.

Of the different types of maintenance the space station will require, the most challenging will be external maintenance performed by specially suited space-walking astronauts. (See fig. 1.2.) NASA refers to this work as extravehicular activity (EVA). EVA crews will leave the pressurized modules of the space station for about 6 hours at a time to maintain the station's external components. As currently planned, each two-person crew will provide up to 12 crew-hours of work time on each 6-hour space walk.

Figure 1.2: Astronauts Performing EVA



Source: NASA.

Space station EVA maintenance will mostly involve the removal and replacement of failed components. Only a limited amount of preventive maintenance or component repair is anticipated. Thus, for a typical EVA, the crew would leave the airlock, acquire the necessary tools and spares, remove and replace components at different work sites, stow failed components and tools, and then return to the airlock.

The amount of EVA that NASA can support is limited by a variety of factors, including the number of flights that the space shuttle can make and the amount of weight it can carry; the limitations of the space suits and related equipment; the physical limitations of the crew; and other demands on the crews' time. In addition, EVA is inherently risky given the harsh and unforgiving environment of space. Among the risks of performing EVA are those related to a failure of the suit, separation from the spacecraft, exposure to radiation, strikes from space debris, and decompression sickness (the "bends").

Evolution of NASA's EVA Maintenance Estimates

Because of the limits on EVA availability, NASA has taken steps to (1) identify the types of external maintenance requiring EVA, (2) estimate the amount of EVA time (expressed in crew-hours per year) that such maintenance will take, and (3) identify ways to reduce EVA requirements, for example, through the use of robotics.

Most of NASA's EVA maintenance estimating efforts have used a computer model, the Reliability and Maintainability Assessment Tool (RMAT).[2] RMAT and its inputs have been refined over time, but its approach remains fundamentally the same. RMAT simulates the assembly and operation of the space station, predicts when component failures will occur, and groups maintenance tasks that can be accomplished during an EVA. One RMAT output is the predicted number of EVA crew-hours NASA expects its astronauts will have to spend performing EVA maintenance actions.

In late 1989, NASA estimated that external maintenance of the completely assembled space station would require 1,732 EVA crew-hours each year. This is equivalent to approximately 144 two-person EVAS, or almost 3 EVAS each week. When NASA made this estimate, it had a goal of less than 1 EVA per month, or a total of 132 EVA hours for maintenance each year—1,600 hours fewer than the predicted requirement.

[2]NASA also is using RMAT to develop its estimates of internal maintenance requirements.

To resolve the discrepancy between the estimate and the goal, NASA established the External Maintenance Task Team in December 1989. This team's July 1990 report, often referred to as the Fisher-Price report after the team's chairmen, William Fisher, a former astronaut, and Charles Price, a NASA robotics expert, estimated an annual requirement of 3,276 EVA crew-hours and recommended a series of actions to reduce that demand. The Fisher-Price team's estimate was calculated using a very early version of what is now the RMAT model.

NASA also established the External Maintenance Solutions Team to (1) identify and analyze the primary sources of external maintenance demand on the space station, (2) propose specific solutions to the external maintenance problem, and (3) assess the technical feasibility of the candidate solutions. This team estimated in January 1991 that if certain maintenance-reducing actions were taken, maintenance on the space station would require only 485 EVA crew-hours per year.

About the same time, NASA completed a congressionally directed redesign of the space station to its current configuration. NASA's first estimate of EVA maintenance demand for the redesigned space station predicted that the EVA requirements would be as few as 200 and no more than 400 crew-hours per year.

NASA's Current Estimate

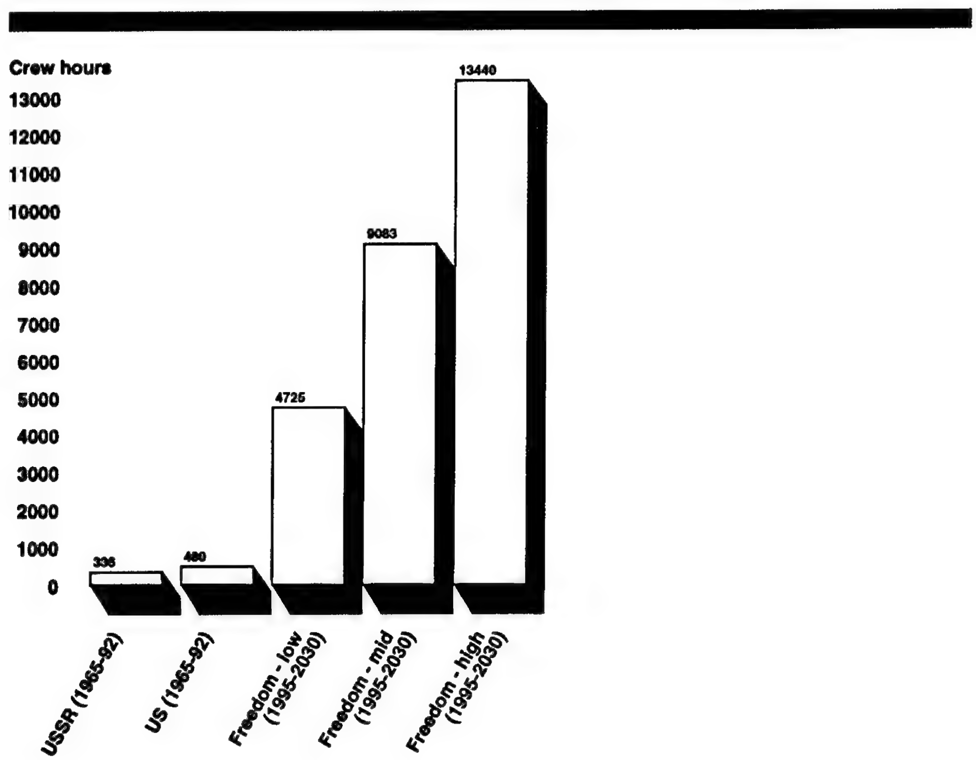
NASA's most recent estimate is that external maintenance may require an average of 135 EVA crew-hours per year, in a best-case scenario. In its worst-case scenario, NASA's average annual estimate is as high as 384 EVA crew-hours. In other words, maintenance EVAS may be required less than once each month or as often as 2.5 times each month over the life of the space station.

In its best-case scenario, NASA assumes that some external maintenance will be performed using remotely controlled robots and that its EVA maintenance crews will have an apparatus available for carrying spare components so that several replacements can be accomplished without having to individually retrieve the spares for each maintenance action. This scenario also uses an RMAT option called "early failures and reliability growth." This feature models an increase in the probability of failure in the space station's early years, but reduces it in the later years to an extent that more than offsets the earlier increases, resulting in an overall reduction in the probability of failure.

NASA's worst-case scenario assumes that neither robotics nor the special carrier is available. Also, it assumes that early failures and reliability growth are not experienced. Program officials believe that a scenario such as this is unlikely to develop because robotics are included in the program and there likely will be opportunities to improve component reliability throughout the station's operating life.

Even under NASA's best-case scenario, the total amount of EVA time required over the life of the station is unprecedented—estimated at nearly 10 times the amount of EVA performed so far by U.S. astronauts. Figure 1.3 compares the total EVA experience of U.S. astronauts and the former Soviet Union's cosmonauts with the low, middle, and high EVA maintenance estimates for Space Station Freedom.

Figure 1.3: Predicted EVA for Space Station Maintenance and Cumulative EVA Hours for Other Space Activities



Factors Contributing to the Decrease in EVA Estimates

NASA's estimates for EVA maintenance have dropped sharply since the Fisher-Price estimate in 1990. NASA's current best-case estimate of 135 EVA crew-hours per year is about 4 percent of Fisher-Price's estimate of 3,276. Space station program officials believe differences between the current

and previous estimates are principally due to such factors as the redesign of the space station to a smaller, less complex facility; the program's adoption of a number of Fisher-Price recommendations for reducing maintenance requirements; and limitations in the development of the Fisher-Price estimate.

According to program officials, the most important factor causing the difference between the current and earlier estimates was the change in the station itself. Within a few months of the Fisher-Price report's publication, the Congress directed NASA to reduce the size and complexity of the space station in order to decrease its cost and to enable it to be used even as it is being assembled. In March 1991, NASA reported to Congress the results of its efforts to scale back the space station design.

The redesigned space station reflects NASA's intent to reduce the amount of EVA necessary for maintenance. The Fisher-Price report contained over 100 recommendations to reduce EVA maintenance, and program officials said they considered and incorporated many of these in redesigning the station. While the reductions in the EVA requirements cannot be precisely determined for each change made in the station's design, program officials generally point to the decrease in the total number of external components and improved accessibility to them as key factors. For the current station design, the number of parts requiring EVA maintenance is estimated at about 3,600, about 1,000 fewer than for the earlier space station design. Of these 3,600 components, about 800 are expected to require routine maintenance. NASA calls such parts "orbital replaceable units." The remainder, called "additional maintainable items," are expected to require maintenance far less frequently.

Program officials cited certain limitations of the Fisher-Price team's work. For example, the team had a limited amount of time (about 6 months) in which to complete and report on its work and was required to work with preliminary data that had not been formally approved by the program office. In some instances, external components already deleted from the program were counted, and some components were counted more than once because of problems in the part-numbering and description system.

Finally, program officials noted that the Fisher-Price work was not intended to produce precise estimates of EVA maintenance requirements, but to serve as the starting point for an ongoing process of estimating and identifying methods of reducing the amount of EVA maintenance. Many of the participants of the Fisher-Price and External Maintenance Solutions

teams are still involved in maintenance planning for the space station and are continuing to refine the work initiated by those teams.

Objectives, Scope, and Methodology

At the request of the Chair of the Government Activities and Transportation Subcommittee, House Committee on Government Operations, we reviewed NASA's efforts to determine the EVA requirements for maintaining the space station. Specifically, our objectives were to (1) assess the reliability of NASA's current EVA maintenance estimates and (2) examine NASA's plans to meet the estimated EVA maintenance requirements.

To accomplish these objectives, we

- interviewed NASA officials and space station contractor personnel and reviewed pertinent documents they provided;
- interviewed reliability engineers outside of NASA (from the U.S. Air Force's Rome Laboratory, Griffiss Air Force Base, and the Space Department at Johns Hopkins University's Applied Physics Laboratory);
- interviewed selected individuals involved in earlier NASA efforts to estimate EVA requirements for the space station; and
- conducted limited evaluation of the RMAT's logic and primary mathematical formulas.

We did not perform an in-depth review of individual component failure rates or removal and replacement times. We limited our review of these data to an examination of the processes used to develop and screen them.

We performed our work at NASA Headquarters in Washington, D.C.; the Space Station Freedom Program Office in Reston, Virginia; and the Johnson Space Center in Houston, Texas.

We conducted our review from November 1991 to July 1992 in accordance with generally accepted government auditing standards. As requested, we did not obtain written agency comments on this report. We did, however, discuss the issues in this report with space station program managers, who generally concurred with our findings. We have incorporated their comments where appropriate.

Validity of External Maintenance Requirements Is Uncertain

NASA has limited assurance that its current component failure rates and replacement times, the primary data used in estimating EVA maintenance requirements, are reasonably accurate. Much of the uncertainty is related to the early development stage of the program and the inherent limitations of the available techniques used to estimate component failure rates and replacement times. As additional data become available over time and are factored into the estimating process, some of the estimating uncertainty will be eliminated. However, NASA could increase its confidence in the estimates by broadening the scope and depth of its review of the failure rate and replacement time data provided by contractors.

Accuracy of Component Reliability Estimates Is Uncertain

The accuracy of any computer model's results depends largely on the validity of its inputs. The validity of component failure rates, a key input to the RMAT model, is uncertain due to the inherent limitations of reliability prediction and the early design stage of many of the components. NASA uses an overall adjustment factor to overcome some of these limitations. However, the factor is lower than that used in previous estimates; therefore, the margin for error provided by the adjustment factor has decreased.

Failure Rate Prediction Techniques May Not Accurately Estimate Actual Performance

Because space station components are of new design, NASA has no historical data to predict their reliability. Therefore, NASA uses standard reliability prediction techniques to estimate their failure rates. Most failure rates for the space station's components are based on the models contained in Military Handbook 217, "Reliability Prediction of Electronic Equipment."[1]

The accuracy of failure rates produced by Military Handbook 217 is uncertain because of the models' inherent limitations. One limitation is that the failure rates are point estimates for which no statistical confidence intervals are available. In other words, NASA does not know how much the actual failure rate could vary from the estimate for a specific component. According to a 1978 study, "Predicting Cost/Reliability/Maintainability of Advanced General Aviation Avionics Equipment," conducted for NASA by the Rand Corporation, field reliability can be considerably less than contractor-predicted values. The study also concluded that Military Handbook 217 methodology could be misused to provide "extravagant" reliability estimates. Although the study is dated,

[1]Failure rates for other types of components are based on sources such as the "Nonelectronic Parts Reliability Data," published by the Department of Defense's Reliability Analysis Center in Rome, New York.

independent reliability engineers we spoke with said its findings were still valid and the same concerns exist today.

NASA program officials agreed that the accuracy of individual component failure rates is questionable. However, they believe that some failure rates would be low while others would be high; thus, in a large system the discrepancies would tend to even out, and the overall result would be reasonably accurate. Furthermore, they believe the failure rates are conservative, because they treat degraded performance as a failure requiring a replacement, even though the component may still be functioning and not need replacement.

Adding to the uncertainty of the failure rate predictions is the early design stage of many of the components. Because of the early stage of design, reliability predictions may be based on preliminary analyses, since insufficient information is available to conduct more sophisticated analyses. However, as component designs mature, better predictions become available and are incorporated into NASA's estimating process. In addition, failure rates may also change if components are redesigned because NASA deems their failure rates unacceptably high.

Adjustment Factor Has Been Lowered

Reliability predictions may not accurately forecast how components will perform once in operation because they do not account for a number of factors, including the operating environment of the components, design flaws, and software problems. In an attempt to overcome some of the limitations of reliability predictions, NASA accounts for other factors—K-Factors—that may increase maintenance demand. K-Factors are intended to supplement a component's failure rate estimate and to account for other failures, such as human- or equipment-induced failures, that are expected to occur. When the maintenance work load predicted by the failure rate is multiplied by a K-Factor, the result is intended to be a more realistic prediction of maintenance needs.

The Fisher-Price study noted that the aerospace industry typically uses a K-Factor value of about 2.0, meaning that the actual maintenance demand can be expected to be double that predicted by the failure rate alone. Fisher-Price attempted to refine this factor. In doing so, they examined historical data on U.S. Air Force aircraft equipment maintenance and identified four K-Factor components: K-1 (failures caused by human error); K-2 (failures caused by the operating environment); K-3 (failures caused by the failure of other components); and K-4 (false alarms,

incorrect fault isolation, or the need to remove one component in order to gain access to another).

The Fisher-Price team developed an overall K-Factor value of 2.02, very close to that used by the aerospace industry. The team found that human-induced failures and dealing with false alarms and incorrect fault isolation caused the greatest increase in the maintenance demand. The team was emphatic about the reasonableness of the K-Factor values it developed and stated that

> K-Factor is shown to be a substantial factor when considering total maintenance demands. . . . The methodology used to develop the equipment type K-Factor values was based on a solid approach. . . . It can be stated with a high level of confidence that if the K-Factor evaluations were performed down to a specific equipment level (i.e., a unique K-Factor value for an antenna, valve, heat exchanger, cable, etc.), . . . the overall results would not change more than a few percent.

Subsequent to the Fisher-Price study, NASA conducted four additional analyses of the K-Factor using data on the maintenance activities for the space shuttle. Program officials considered the space station to be more analogous to this experience than to that of Air Force aircraft. Table 2.1 shows the five K-Factor estimates that have been made.

Table 2.1: K-Factor Values Developed by Various NASA Analyses

K-Factor Analysis	K-1	K-2	K-3	K-4	Total[a]
July 1990, Fisher-Price	0.53	0.14	0.01	0.34	**2.02**
July 1990, EMST[b]	0.39	0.17	0.01	0.15	**1.72**
December 1990, EMST[b]	0.10	0.17	0.01	0.18	**1.46**
May 1991, contractor-developed	0.10	0.06	0.01	0.32	**1.49**
Current, derived from earlier estimates	0.10	0.17	0.01	0.16	**1.44**

[a]Total for each row is 1 plus the assigned values of K-1 through K-4.

[b]External Maintenance Solutions Team.

With one exception, the total K-Factor has decreased in each successive analysis. We could not objectively assess the derivation of the K-Factors for any of the five analyses because, even though the K-Factors were derived from historical data, the values were subjectively determined. However, we did obtain program officials' explanations of the major K-Factor reductions.

The greatest reduction within the individual K-Factors was for the human error component (K-1). Program officials contended that the contribution of K-1 to maintenance demand is less than that reported on Air Force aircraft. The officials attributed the difference to several factors. First, the space station components will be designed to minimize human-induced damage during maintenance operations. In addition, officials believed the NASA crews' training and motivation to be higher than that of Air Force aircraft mechanics. Finally, they said that the environment within the space suit is more comfortable than the working environments in which aircraft mechanics frequently find themselves. As an example, they cited the difficulty of performing maintenance tasks in the cramped compartments of an aircraft on a hot day. Based on these premises, program officials assume that fewer failures caused by human error will occur while maintaining the space station. Therefore, they have assigned a lower value for K-1 than did the Fisher-Price team.

The total value NASA has currently assigned to the K-1 Factor (0.10) is the same as the value that Fisher-Price attributed solely to the additional difficulty associated with working in space. NASA's current K-1 value is intended to cover not only that difficulty, but also equipment misuse, incidental contact, damage caused during maintenance, and other potential human errors. For those eventualities, Fisher-Price added an additional factor of 0.43.

Regarding the K-4 Factor, NASA assumes that the space station will experience fewer problems than the Air Force with false alarms or incorrect fault isolation. The redesigned station will have reduced automatic testing, fault detection, and fault isolation on noncritical items, making it more difficult to detect and locate failures. However, program officials believe the number of maintenance actions undertaken as a result of false alarms or incorrect fault isolation will be minimized because spares will generally not be on board the station when a failure is indicated. Therefore, maintenance will not occur until the spare can be delivered by a visiting space shuttle. In the meantime, the station and ground crews will work to identify whether an actual failure occurred and, if so, where.

In addition to the four K-Factors currently used, a contractor who examined K-Factors for NASA identified a fifth. The contractor recommended that NASA add a K-5 Factor to account for failures that result from errors in processing station components (for example, handling and transporting). According to the contractor, this factor accounted for an

increase of about 10 percent in the maintenance demand for the space shuttles. In examining shuttle maintenance, the contractor noted, "Most shuttle problems had minimal impact on operations because most were discovered during ground operations when corrective resources were available. This luxury will not be available on-orbit." While program officials believe that component inspection and testing prior to launch will reduce the problems related to processing and, therefore, do not use K-5, it is unclear that the need for a K-5 Factor can be completely eliminated.

According to program officials, K-Factor values are still being reviewed and may be reduced even further.

Time Required for Maintenance Actions and Related Activities Is Not Yet Proven

A replacement time estimate consists of two factors, an estimated work site time and overhead activities. Work site times are estimates, generated by contractors, of the time it will take an astronaut to remove and replace a failed external component. Work site time estimates may be based upon on-orbit experience or simulations on the ground for similar tasks. Current work site time estimates are preliminary, and thus uncertain, given the incomplete design status of many of the station's components.

Overhead activities include traveling to a repair site and gathering the appropriate tools and spares to make the repair. NASA's current estimates for overhead times are significantly lower than those used in earlier space station maintenance estimates. The lower estimates reflect, in part, NASA's adoption of many of the Fisher-Price study recommendations regarding the reduction of overhead.

Accuracy of Replacement Time Estimates Is Uncertain

Because NASA does not yet have all the external space station component "mock-ups" needed for training, many component removal and replacement times are based on a variety of sources that may or may not have direct relevance to the space station. The estimates should improve after NASA has the mock-ups needed to time the simulation of specific activities, such as replacement.

The early design status for many of the components creates uncertainties about the time required to remove and replace them. With critical design review for the crew-tended capability phase planned for the summer of 1993, the design for many space station components is incomplete. For each such component, NASA predicts the steps that will be required to replace it and how long these steps will take. As the design of a

component evolves, so will its replacement time estimate. In addition, replacement time estimates that NASA deems excessive may trigger a redesign of the component.

Space station contractors provide NASA with replacement time estimates for each component. Some of these estimates are based on "bench-time" on earth, with time added on to account for the difficulty of performing the same task in space. Other estimates are based on similar maintenance tasks conducted on orbit or simulated in the Weightless Environment Training Facility[2] or with computers, or are based on engineering estimates. However, very few maintenance tasks have been simulated either in the weightless training facility or through the use of computers. At present, simulations in the weightless training facility have been conducted mainly for assembly tasks. Maintainability testing has been conducted primarily to determine if a particular task can be performed by an astronaut wearing a space suit—not for the purpose of determining how long the task will take.

NASA has not explicitly accounted for the possibility that removal and replacement tasks take longer than predicted. Task time growth can result in a significant increase in the amount of EVA time required, as was illustrated recently during the May 1992 space shuttle Endeavour's mission to capture, repair, and re-launch a communications satellite. NASA had scheduled the rescue operation as a single two-person EVA lasting approximately 6 hours (or 12 crew-hours). It actually required three separate EVAs, including a first-ever three-person EVA, totaling approximately 44 crew-hours—almost four times NASA's prediction.

Program officials viewed this experience as an imperfect analogy because the satellite was not designed to be captured or repaired. They also pointed out that although capturing the satellite took far longer than anticipated, the repair task took about half the time predicted. In contrast, the astronauts on that mission acknowledged that their experience demonstrated the need to take a second look at NASA's ability to accurately predict how people and systems interact in space. Indeed, on the basis of the Endeavour experience, the NASA Administrator was considering adding as many as three EVAs to already scheduled space shuttle missions to provide the astronauts with more time to practice space station-related activities while on orbit.

[2]The facility, located at the Johnson Space Center near Houston, Texas, allows astronauts to train for missions in simulated zero-gravity conditions.

Overhead Times Have Been Lowered

EVA overhead refers to all EVA activities not directly related to the actual removal and replacement of an external component. Overhead activities include leaving and reentering the airlock, traveling to and from the work site, and retrieving and stowing tools, spares, and the failed components. The Fisher-Price team estimated that within a 6-hour EVA, 5 hours would be overhead and 1 hour would be work site time. The team compared the results of this study with actual EVA experience on the space shuttle and on the Skylab space station. In addition, the team performed engineering evaluations of selected aspects of space station overhead activities using space-suited astronauts in the Weightless Environment Training Facility at Johnson Space Center. In each case, a very close correlation was observed between the team's overhead estimates, previous flight experience, and the engineering tests.

The Fisher-Price study contained 20 recommendations for reducing overhead time, and NASA has adopted many of them. For example, NASA has located about 60 percent of the space station components for easy access by EVA crew members. In addition, NASA adopted the recommendations that allow the EVA crew members to work independently of one another and to carry the spares necessary to perform several maintenance tasks without needing to retrieve each spare individually. On a typical 6-hour EVA, NASA now expects each EVA crew member to spend about 3 hours on work site activities and about 3 hours on overhead activities. However, until overhead activities have been tested or verified on orbit, it is not certain that NASA can achieve this predicted overhead rate.

RMAT Provides Some Margin for Error

Program officials agreed that component replacement times and the overhead associated with performing maintenance are uncertain. However, they believe that RMAT predictions of EVA maintenance requirements have built in conservatism that lowers the probability that more time will be needed than the model predicts. This conservatism derives from two aspects of the model, both of which officials categorize as "scheduling inefficiencies."

When RMAT schedules maintenance tasks, it generally queues the tasks in the order of their criticality to space station operations. While criticality will be the primary determinant of maintenance scheduling for the space station, EVA crews will also consider which maintenance tasks can be grouped in order to make the most efficient use of their EVA time. RMAT does not group maintenance tasks in the most efficient manner; thus, in

some cases, it generates a greater EVA requirement than may be experienced in actual maintenance operations.

In addition, RMAT generally assumes that an EVA lasts for 6 hours, but will allow the EVA to extend up to 6 hours and 15 minutes, if needed, to perform a final task. However, if the performance of that task would cause the simulated EVA to last beyond 6 hours and 15 minutes, RMAT assumes that no part of the last task is performed. Program officials estimate that the effect is an inefficiency of about 20 percent in RMAT's scheduling of maintenance tasks. The officials said that, in reality, the EVA crew member would complete the last task by performing a longer EVA, would perform some part of the task, or would perform an entirely different maintenance action to maximize the use of the EVA.

Although the scheduling inefficiencies lower the probability that actual maintenance requirements will exceed those NASA currently predicts, it is unclear whether the margin provided is sufficient to accommodate the degree to which the failure rate and replacement time estimates could be understated. As discussed, NASA does not know how much the actual failure rates could vary from the estimates because no confidence intervals are available. In addition, very few component replacement times have been validated.

NASA's Review of Model Input Data Is Inadequate

The scope and depth of NASA's review of the reliability and maintainability data submitted by contractors are insufficient to ensure their quality. According to officials at two of the three NASA centers that are primarily responsible for developing the space station, there is limited detailed review of reliability and maintainability data provided by the contractors.[3] Program officials contend they do not have adequate resources to perform a broader, more detailed review of the data.

At both centers, several organizations, including personnel from Systems Engineering and Integration; Safety, Reliability, and Quality Assurance; and the Space Station Project Office, review the contractor-generated reliability and maintainability data before they are released to the rest of the space station offices. However, only one center's contractor routinely identifies its sources of information and the assumptions it uses to develop

[3]Three NASA centers, Marshall Space Flight Center in Alabama, Johnson Space Center in Texas, and Lewis Research Center in Ohio, have responsibility for overseeing the work of the contractors that are building the space station. We did not speak with Marshall Space Flight Center officials about EVA maintenance because that center's part of the station has relatively few external components and is not a major source of EVA maintenance requirements.

reliability and maintainability estimates. The other center's contractor provides such information only when specifically requested, even though the identification of data sources and underlying assumptions is deemed by NASA and outside experts to be important in assessing the validity of the data.

Officials at both centers said that because of insufficient resources, they do not verify every number that the contractor provides. Instead, they perform what they termed "sanity checks." Items that receive attention are those that, based upon experience, appear questionable. For example, a big change in the numbers compared with a previous data set would warrant a closer look. Failure rates that appear too high or too low might also trigger a review. If there are concerns about the data, the review team sends a list of questions to the contractor, which must provide answers. Neither centers' review assures coverage of items with low or medium impact on EVA maintenance demand, although officials maintained that all high-demand and critical items are reviewed. Officials agreed that data that appeared satisfactory, but were in fact erroneous, would not be reviewed and would, in effect, "fall through the cracks."

A reliability engineer at an Air Force laboratory specializing in advanced electronics research said that in his work on development programs, he performs detailed reviews of representative samples of contractor-provided reliability data. He said that he has found that contractors often use optimistic assumptions and perform incomplete analyses in developing these data. A reliability engineer at the Applied Physics Laboratory of Johns Hopkins University said that he has seen a tendency by contractors to manipulate the data to arrive at an acceptable result without making changes to the hardware.

Other Uncertainties

Some EVA maintenance requirements are not yet included in NASA's estimates. For example, for the components produced by the international partners, the data base for NASA's computer model includes reliability and maintainability data only for the Canadian Space Agency's components. No data have yet been included for components developed by the European Space Agency or the Japanese National Space Development Agency. However, NASA program managers do not expect the European and Japanese components to contribute significantly to EVA maintenance demand. In addition, NASA has not considered any EVA time that may be required later in the program to add shielding to the station to protect it from orbital debris.

On the other hand, program officials add 20 percent to the overall estimate of EVA maintenance requirements to provide for the possibility that external components for which no requirement has yet been identified may need to be added to the space station. In addition, program officials add 10 percent for preventive maintenance even though the station is designed to minimize the need for such maintenance. In both cases, program officials think that the additions should be sufficient to meet any requirements that may arise.

Conclusions

Given the limitations of reliability prediction, the reduction in the margin for error accompanying NASA's use of lower K-Factor values and decreased overhead rates, the limited review given to contractor-provided data, and other uncertainties, actual EVA maintenance demand may differ significantly from NASA's current predictions. However, some of the uncertainties surrounding NASA's current estimates are likely to be resolved as component designs mature and better data are incorporated into the estimating process.

Notwithstanding the potential for resolving some of the uncertainties over time, NASA could increase its confidence in the estimates by improving its reviews of contractor data. NASA officials have said they do not have the resources to perform more extensive reviews. However, such reviews are standard engineering practice and are especially important for a program of the unprecedented size and complexity of the space station. In the absence of a more detailed review process, NASA cannot be certain that the space station contractors are providing credible estimates based on reasonable sources and assumptions. A review that provides more thorough coverage in terms of both scope and depth could increase NASA's confidence in its data.

Recommendation

We recommend that the NASA Administrator direct that contractor data used to develop EVA maintenance demand estimates be reviewed in sufficient scope and depth to provide better assurance of their accuracy.

Extensive Maintenance Backlog Could Accumulate During Assembly of the Space Station

EVA resources will be insufficient to address all the external maintenance needs that may develop during the station's assembly phase, and an extensive backlog of maintenance actions could accumulate. Maintenance planners have not yet completed their analyses of the potential impact of the backlog on the station's performance; thus, even though they have predicted the total EVA maintenance work load, they do not yet know which maintenance needs can be postponed.

NASA may have underestimated the potential size of the maintenance backlog. Maintenance planners assume the availability of EVA resources on the assembly and utilization flights; however, these resources are not currently committed for maintenance. If EVA maintenance is necessary on assembly flights, it could delay some assembly tasks. Similarly, performing EVA maintenance on utilization flights could affect the station's research usefulness. Ultimately, if sufficient EVA maintenance time is not available on assembly and utilization flights, shuttle flights would need to be added specifically for maintenance, an action that would increase program costs and also delay assembly and use of the station.

After assembly, sufficient time is expected to be available to meet NASA's estimated EVA maintenance requirements. However, actual EVA requirements that exceed predicted levels would reduce the amount of time available for other activities.

NASA Has Not Yet Determined the Potential Impact of the Maintenance Backlog

When a component on the space station fails, NASA may have the option of postponing the maintenance required to remove and replace it. Deferring some maintenance will be possible because of the "redundancy," or backup capabilities, built into space station systems. In the early assembly stages, there will be limited redundancy. Therefore, failures during this period have the greatest potential to disrupt operations of the station and, thus, may require immediate attention.

Program personnel, however, have not yet completed an evaluation of how unrepaired external components will affect the operations of the space station. That is, they have not determined which combinations of components can fail before an EVA becomes absolutely necessary. Program officials also do not yet know how well the space station will function if the backlog becomes as large as predicted.

According to program officials, analyses to determine how failed components will affect the viability and performance capabilities of the

space station will be completed before the program's critical design review in the summer of 1993. Until those analyses are done, program officials will not know which maintenance needs can be deferred.

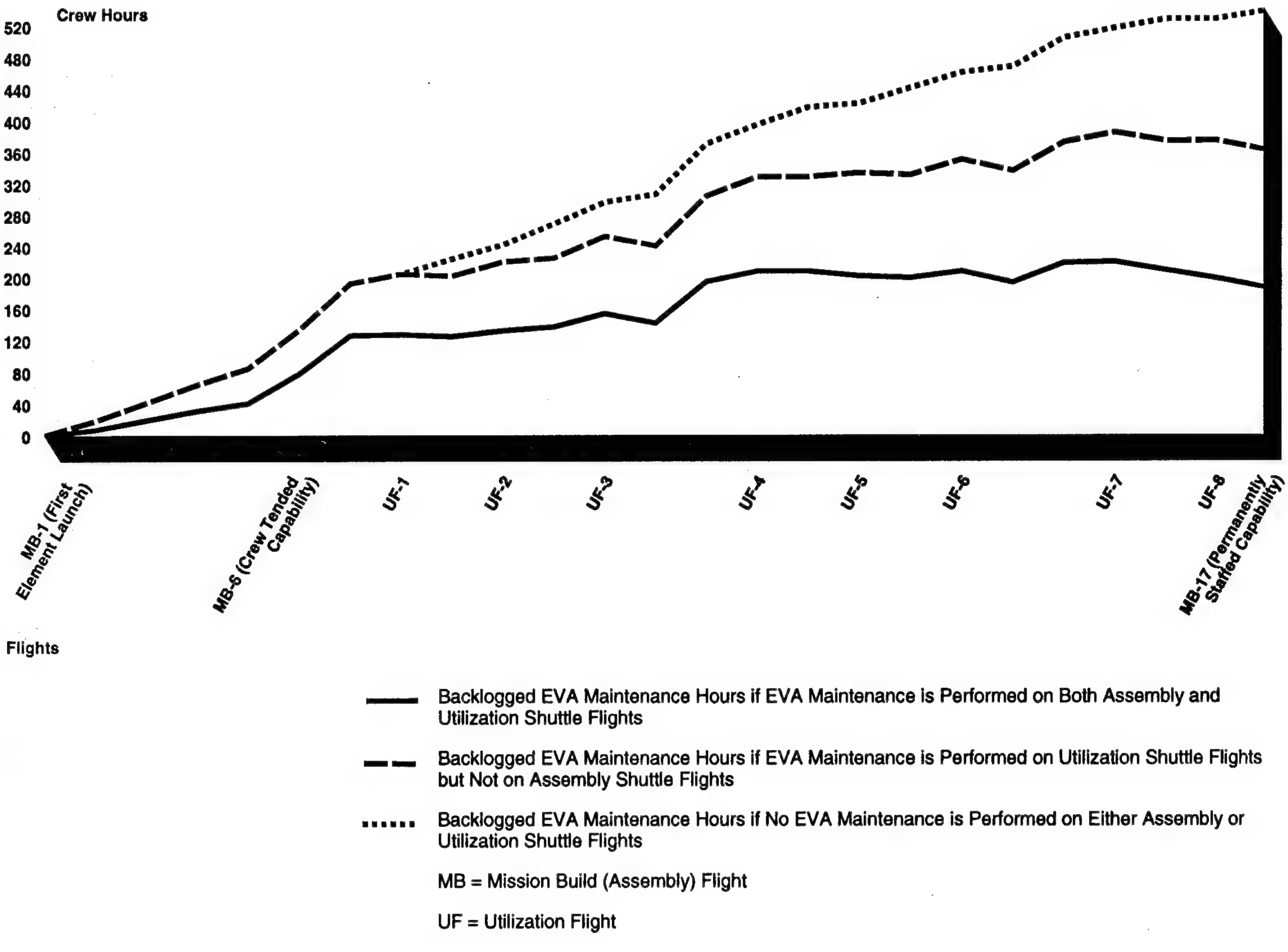
Estimated Backlog May Be Understated

The maintenance backlog could be understated because of assumptions about the availability of EVA maintenance time on space shuttle assembly and utilization flights. The current estimate of the backlog assumes that 12 hours of EVA maintenance will be performed on each assembly flight and 24 hours of maintenance will be performed on each utilization flight. However, the use of EVA for maintenance on these flights is not an approved part of the program.[1] To the extent that any of this assumed maintenance cannot be performed, the predicted backlog is understated.

Assuming 12 hours of EVA maintenance on each assembly flight and 24 hours on each utilization flight, station program officials estimate that the backlog will peak at 220 crew-hours during the assembly phase. We analyzed NASA data and determined that the backlog estimate could be understated by as much as 318 crew-hours if NASA's assumptions prove optimistic. In one analysis, we accepted NASA's assumption that 24 EVA crew-hours would be available for maintenance on each utilization flight, but assumed that no EVA maintenance would be possible on the assembly flights. In the other analysis, we assumed that no EVA maintenance is performed on either the assembly or utilization flights. As shown in figure 3.1, the backlog could be far greater than currently predicted.

[1]According to the Program Management Agreement between the space shuttle and space station programs, the space shuttle program must be able to provide up to 48 hours of EVA (four EVAs) on each assembly flight, exclusively for assembly activities. If 48 hours of EVA were performed on each of the 17 assembly flights, EVA would total 816 crew hours. In general, however, only two EVAs are currently planned for each assembly flight. At this time, no EVA is scheduled for any utilization flight.

Figure 3.1: EVA Maintenance Backlog by Shuttle Flight



While program officials are concerned about the maintenance backlog, they believe that the backlog is unlikely to grow beyond the levels currently estimated. They believe that the backlog predicted is overly pessimistic because it is based on an assumption that during the early years of the station, component failure rates are three times higher than those developed by the space station contractors. By using such an

approach, NASA simulates what it believes to be a worst-case scenario for EVA maintenance while the station is being assembled.

Maintenance and Assembly Assumptions Are Inconsistent

All EVA currently planned during the 17 space shuttle assembly flights is reserved for constructing the space station. Preliminary estimates indicate that assembly may require a total of 374 crew-hours, as follows. NASA has tentatively estimated EVA assembly times for the first 12 flights at an average of 18 hours, 22 minutes each. However, a program official estimates that these times will grow about 20 percent, resulting in an average of 22 hours and 2 minutes per assembly flight. Assuming that similar times will apply to the five other assembly flights, the total EVA time required for assembly would be about 374 crew-hours, or about 46 percent of the 816 EVA crew-hours that the shuttle must be prepared to support for assembly of the station.

Maintenance planners, in estimating the backlog, assumed that some of the EVA time currently designated exclusively for assembling the space station will be used for EVA maintenance. Specifically, they assumed that space shuttle crews on each assembly flight would spend 12 EVA crew-hours, or one EVA, performing maintenance. In contrast, current plans for the first seven assembly flights indicate that NASA will conduct assembly EVAS only—two on each flight, with the exception of the fifth flight, for which three assembly EVAS are planned.[2] As shown in table 3.1, the time remaining for the EVAS currently planned on each of the seven flights is expected to be less than 12 crew-hours.

[2]Current assembly planning documents provide detailed information for assembly only for the first seven assembly flights.

Table 3.1: EVA Crew-Hours Currently Planned for Space Station Assembly on First Seven Shuttle Flights

Assembly flight number	First EVA	Second EVA	Third EVA	Fourth EVA	Time remaining on planned EVAs
MB-1	14:36	4:48	[a]	[b]	7:12
MB-2	13:48	5:26	[a]	[b]	6:34
MB-3	12:34	10:43	[a]	[b]	1:17
MB-4	13:58	11:10	[a]	[b]	0:50
MB-5	17:10	10:46	5:36	[b]	7:38
MB-6	14:53	13:00	[a]	[b]	0:00
MB-7	10:36	9:34	[a]	[b]	3:50

Note: A program official told us that EVA crew-hours needed for assembly were likely to increase by 20 percent. The figures in this table reflect that increase.

[a]A third EVA is not planned on this flight. Twelve EVA crew-hours would be available if the EVA is added.

[b]A fourth EVA is not planned on any of the first seven assembly flights. Twelve EVA crew-hours would be available if the EVA is added.

Maintenance planners said that it will be possible for NASA to add a third and fourth EVA to the assembly flights or to otherwise modify plans if critical maintenance demands require. To add EVA time would involve a weight penalty for two additional crew members,[3] supplies, and replacement components that would be needed. While program officials believe that this weight could be accommodated without affecting assembly operations, they acknowledged the possibility that it might become necessary to delay the launch of some hardware. For example, they said that, if necessary, NASA might move the launch of a laboratory rack from an assembly flight to a utilization flight in order to permit critical maintenance to be performed during the assembly flight.

Assembly planners believe that it may be possible to perform some maintenance during "waiting periods" between assembly tasks. However, no commitment has been made to do this, and it is uncertain that NASA will be able to fit any additional tasks into the assembly schedule. Assembly times are estimates for components that are still in the preliminary design phase and for which assembly operations have not been fully simulated. The actual assembly time needed could vary significantly from NASA's current predictions. Any problems in assembling the space station will

[3]In order to perform 48 hours of EVA, the shuttle crew must include seven crew members. According to current plans, the shuttle crew will have only five members on each of the first seven assembly flights.

begin to absorb any remaining EVA time, reducing the amount that might otherwise be available for maintenance.

In addition, astronauts who have recently performed EVA have cautioned against trying to do too much. In a press briefing, one astronaut from the recent space shuttle Endeavour flight warned, "Go slow. Don't try to sign up for more than you can do. Try not to over-assign yourself." Regarding the tendency to continue adding tasks as the astronauts become more proficient in training, he added, "We're going to recommend [that] folks resist doing that." Another astronaut on the same flight added, "You can't hurry when you're out there. You can never reach the same pace that you can work at in the training facility."

Finally, program officials said that if the space station's critical EVA maintenance needs exceed the amount that can be provided during assembly and utilization flights (a scenario they deem unlikely), space shuttle flights could be added to the program. Adding flights would have a significant impact on the program's cost and schedule and possibly on future shuttle missions unrelated to the space station.

EVA Maintenance Needs May Reduce the Amount of Research Conducted on Utilization Flights

Given the magnitude of the maintenance backlog currently predicted to exist when the eight utilization flights are scheduled,[4] space station maintenance planners assume that NASA will need to perform 24 EVA crew-hours of maintenance on each of these flights. Because no EVA maintenance time is yet allocated on the utilization flights, the amount of time available for research activities may be reduced by the amount of time redirected for EVA maintenance and the associated preparatory activities.

EVA Availability Will Be Less Constrained After Assembly Is Completed

After the 17th assembly flight scheduled for 2000, the space station is expected to be permanently occupied by crews of four astronauts, who will spend their time operating the space station, performing research, performing internal and external maintenance, and taking care of their personal needs. Although there are uncertainties concerning the demand for and supply of EVA maintenance during this period, more EVA resources will be available from both the shuttle and the space station than during the assembly period.

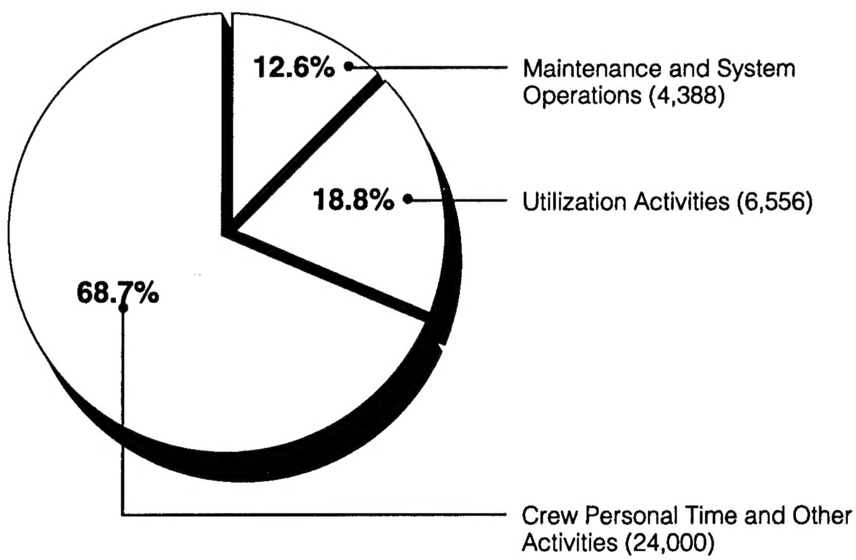
[4]NASA estimates that the backlog will be 127.2 hours at the time of the first utilization flight.

The primary limitations on EVA maintenance time after the assembly phase will be competing demands for the crews' time and the limits on the amount of EVA that the crew of the shuttle can provide during its quarterly visits.[5] The external maintenance demand NASA currently predicts could be accommodated within these EVA limitations; however, if actual requirements exceed the levels predicted, crew time available for other activities would be reduced.

Space Station Crew Time Allocations

Once the space station is completely assembled and permanently staffed, total annual crew-hours available will be about 35,000 (4 crew members multiplied by 8,760 hours per year). All crew time is allocated among various space station activities, as illustrated in figure 3.2.

Figure 3.2: Annual Allocation of Space Station Crew-Hours



About 69 percent of the crew-time (24,000 crew-hours) is allocated to activities such as sleeping, eating, and exercising; crew transfer operations; and other activities. Twelve percent (about 4,390 crew-hours)

[5]In addition to the efforts of astronauts performing EVA, program officials plan to use the space station's robotics equipment to perform external maintenance of the space station. They believe that it may be possible to perform up to half of the external maintenance by the use of robots, although this is not a demonstrated capability. Also, while the use of robots will reduce the amount of EVA, the robots must be operated by an astronaut inside the space station. A task done by a robot requires, on average, three times as long as the same task performed by an EVA astronaut.

is allocated for all types of space station systems operations and maintenance-related activities. This includes 252 crew-hours for EVA maintenance and 329 crew-hours for operating remotely controlled robots to perform some external maintenance. The remaining 19 percent (about 6,550 crew-hours) is allocated to the space station's utilization activities. Any growth in maintenance requirements could reduce the amount of time available for the utilization activities, including life sciences, materials processing, and technology development.

Shuttle Crew Will Perform Some EVA Maintenance After Assembly

After assembly is completed, the shuttle will continue to visit the space station approximately four times each year for the purposes of providing supplies, crew rotation, and maintenance. During these visits, the shuttle crew will perform as much EVA maintenance as possible. Assuming a moderate level of EVA (24 crew-hours per flight),[6] the shuttles would provide 96 hours of EVA maintenance each year. Supporting maintenance from the visiting shuttle will reduce the demand on the EVA-supporting resources of the space station.

EVA Maintenance Requirements After Assembly Is Completed

The first crew to permanently occupy the space station could find a sizeable EVA maintenance backlog. NASA predicts that when permanently staffed capability is achieved, the backlog will be 186 hours. As previously indicated, depending on the availability of EVA maintenance on assembly and utilization flights, the backlog could be much larger. While NASA intends for visiting shuttle crews to perform EVA maintenance to the maximum extent possible, the level that remains for the first space station crew may be sufficiently high to encroach upon the time allocated for other activities.

After the backlog accumulated during the assembly phase has been reduced, NASA's prospects for managing the EVA maintenance backlog should improve. As discussed in chapter 1, NASA is currently estimating that annual EVA maintenance will require, on average, 135 crew-hours (best case) to 384 crew-hours (worst case). The midpoint of this range, approximately 260 EVA crew-hours, is roughly equivalent to NASA's space station EVA maintenance allocation (252 hours). Provided that actual EVA requirements do not exceed NASA's predictions, this amount, when added to the amount of EVA that could be provided by the shuttle and the amount

[6]NASA's recent flight of the space shuttle Endeavour demonstrated unprecedented EVA capabilities, including a three-person EVA and one EVA lasting nearly 8-1/2 hours. However, NASA considers this type of EVA mission to be extraordinary and, for planning purposes, assumes that EVAs of up to 6 hours are performed by two-person teams.

that may be performed using robots, makes the burden appear manageable over the long term.

Conclusions

NASA has not yet committed EVA resources for space station maintenance during the assembly period because its analyses of the impact of the backlog are not yet complete. Such information, expected to be available for the program's critical design review, is needed before NASA can realistically determine which maintenance needs can be postponed until the space station's completion. If critical maintenance needs exceed the amount that can be accomplished on the assembly and utilization flights, shuttle flights may need to be added for maintenance, potentially disrupting the station's assembly schedule, increasing its costs, delaying its early research usefulness, and adding to the cost and schedule of space shuttle missions that are unrelated to the space station.

Recommendation

We recommend that the NASA Administrator direct that, before the completion of the space station's critical design review, appropriate steps be taken to eliminate inconsistent assumptions in maintenance, assembly, and utilization plans concerning the availability of EVA maintenance time during the station's assembly phase.

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